Home
Help

HTS Fault Current Controller Restoration Project

Los Alamos National Laboratory

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FY2001 EERE Project Funding: $1050 K

Annual Peer Review Meeting, August 1-3, 2001
DOE Superconductivity Program for Electric Systems

HTS Fault Current Controller Restoration Project

Brian Newnam:
Introduction and Technology Integration

Xing Yuan (IGC-SuperPower):
Utility Applications of HTS Fault Current Controllers

Heinrich Boenig and Joe Waynert:
HTS Fault Current Controller Restoration

High-Temperature Superconducting Fault Current Limiter

Partners:

General Atomics: *System integrator, power electronics, control, cryogenics, testing, marketing*

Intermagnetics General Corp.: *HTS wire and coil, cryogenics*

Los Alamos National Laboratory: *Power electronics, control, cryogenics, testing*

Southern California Edison: *Host utility, power systems, testing*

High-Voltage Breakdown Precluded Completion of 1999 Demonstration Tests of FCC Operation at SCE Substation

SPI ended and DOE contracted with LANL to:

- **Evaluate extent of damage**
- **Repair and modify, if feasible, and**
- **Perform high-voltage and integrated FCC tests using Los Alamos 13.4 kV substation**

If successful,

- **Arrange for field testing at SCE substation**

Technology Integration (Scoring Criterion)

Los Alamos ***(High power tests, HV bus design, power electronics, control, cryogenic engineering)***

is collaborating with team members:

- **IGC-SuperPower** ***(HTS coils, high power tests, marketing)***
- **General Atomics** ***(Electrical and cryogenic test support)***
- **Magtec Engineering** ***(System failure evaluation)***
- **Texas Tech University** ***(HV insulator tests)***
- **Southern California Edison** ***(Host electrical utility)***
- **Cryomech, Inc.** ***(Cryogenic systems)***
- **DOE-Golden Office** ***(Program support)***

SuperPower LLC
A Subsidiary of Intermagnetics General Corporation

Utility Applications of HTS Fault Current Controllers: Mitigation of Excessive Fault Currents in Distribution Substations

Xing Yuan
IGC-SuperPower, LLC

Annual Peer Review Meeting, August 1-3, 2001
DOE Superconductivity Program for Electric Systems

HTS FCC Benefits to Utility Are Extensive

- Accommodation of new generation facilities, independent power producer (IPP) hookup and power import without having to upgrade existing grid protection equipment

- Elimination or deferral of the construction of new substations, bus splitting, and line equipment upgrades in short-circuit over-duty situations

- Enhancement of:
  - System safety
  - System stability
  - Power quality
  - Reliability

Case Study of an HTS FCC Application

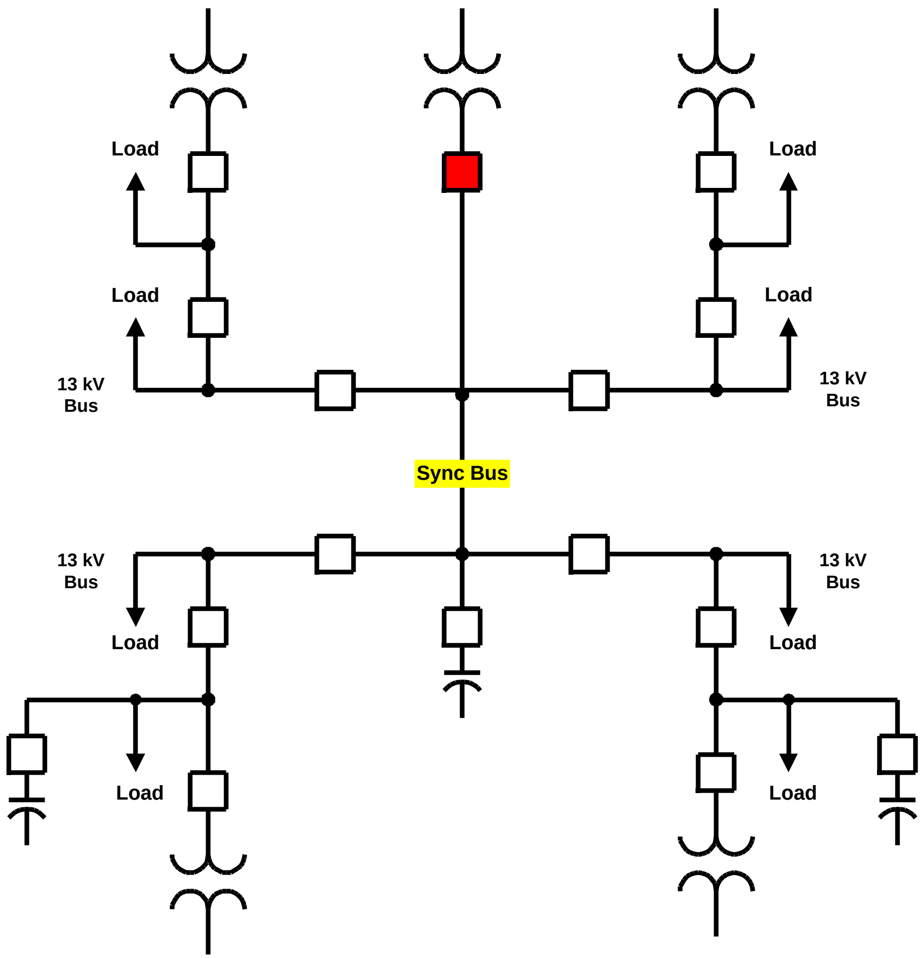
Case Study:
Correction of a Serious Fault Over-Duty Problem

- **Four-transformer H-bus configuration (a spare fifth transformer is unconnected)**
- **Present condition: Available fault is 14% (to 40%) higher than the breaker rating**
- **Goals:**
  - **Fault duty reduction**
  - **Ability to connect the spare (5^{th}) transformer**
  - **Ability to operate with 3 ~ 5 txf configurations**

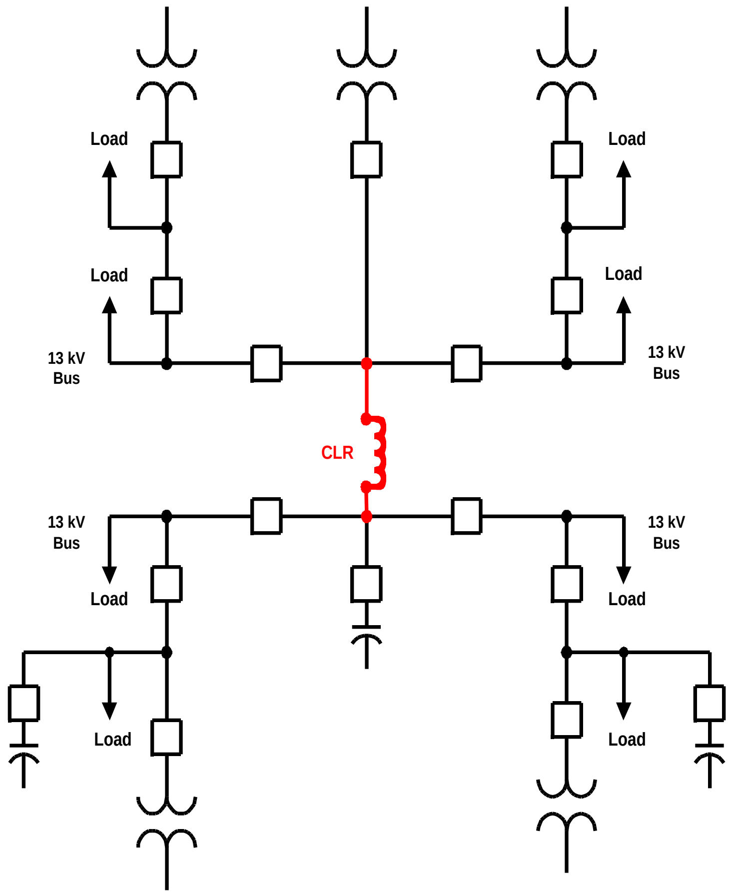
IGC SuperPower LLC

A Subsidiary of Intermagnetics General Corporation

Example: Only 4 of 5 Transformers Are Connected

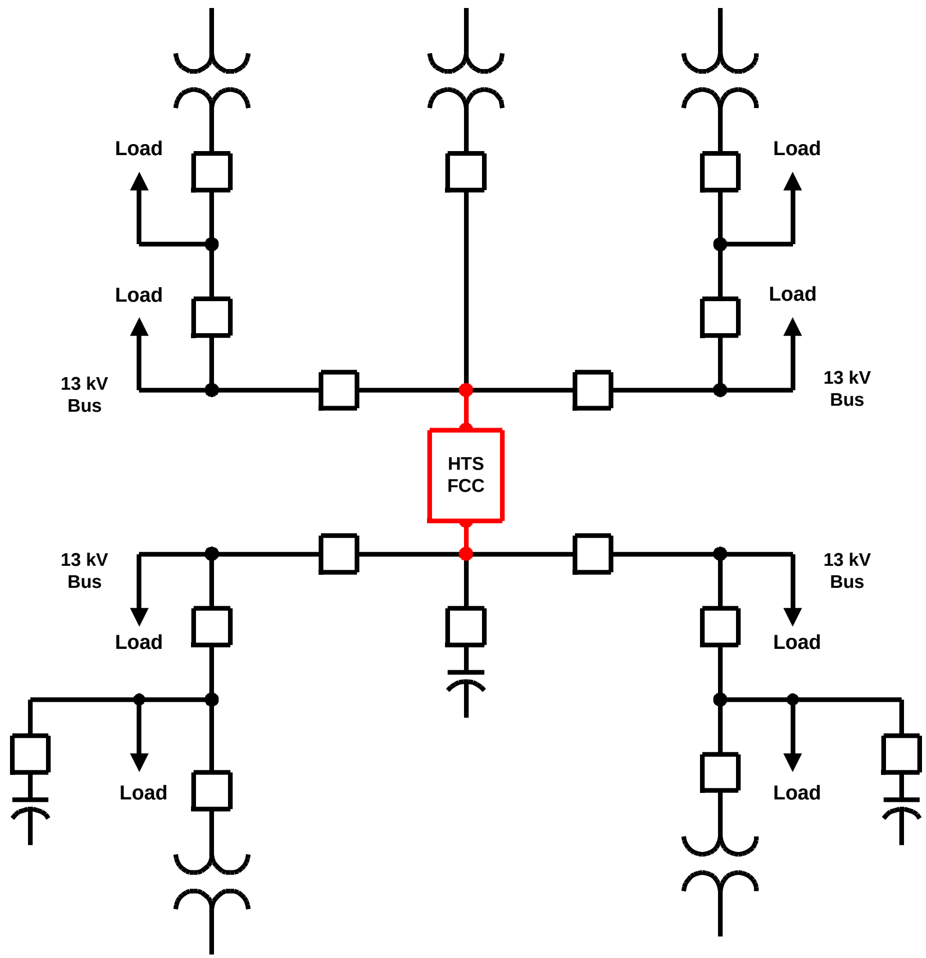


A Current Limiting Reactor (CLR) Is Not a Solution



- **Serious system-wide problems created when CLR is applied:**
  - **Up to 20% system voltage drop**
  - **Circulating current in the transformers**

An HTS FCC Is THE Solution



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HTS FCC's Provide an Excellent Technical and Economical Solution for Electric Utilities

- **Reduces the available fault to a safe level**
- **Increases the substation capacity substantially**
- **Allows flexible operational configurations (3 to 5 transformers)**
- **Improves system stability, reliability and power quality**
- **Millions of dollars in potential economic benefit to utility**

HTS Fault Current Controller Restoration

Contributions by

Los Alamos National Laboratory

presented at

2001 DOE Annual Peer Review

Washington, DC   August 1-3, 2001

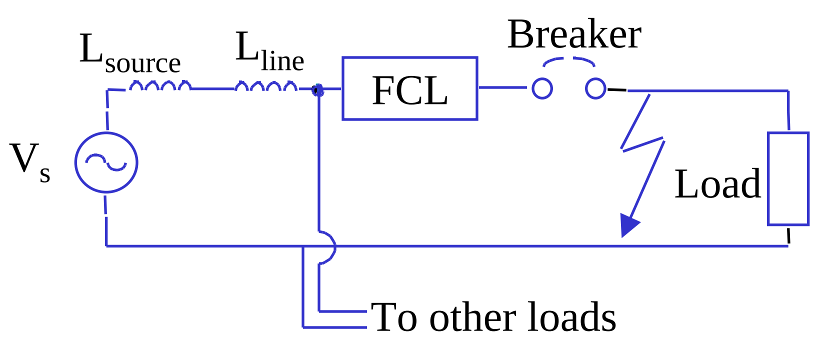
Heinrich Boenig and Joe Waynert

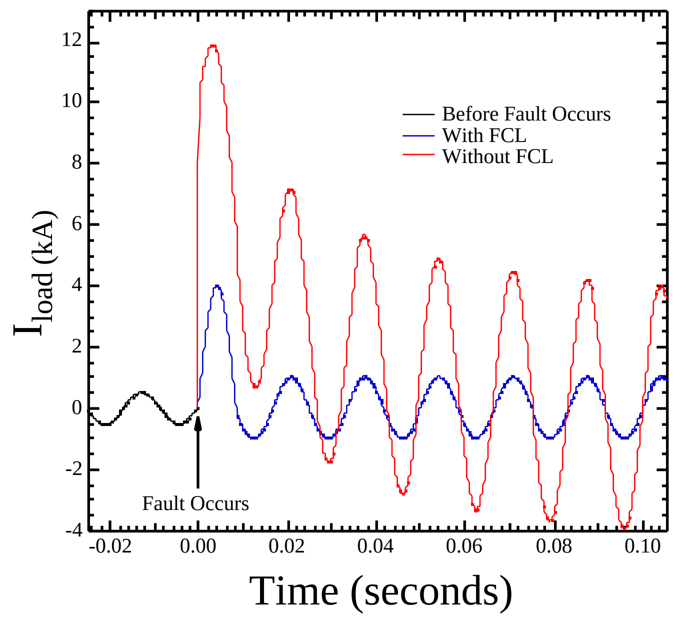
Outline of Talk

1. Principle of fault current limiter (controller) operation
2. Approach of restoration program
3. Result of visual inspection
4. Failure cause evaluation
5. Cryogenic and vacuum system
6. New high voltage bus design
7. Tests planned at Los Alamos
8. Schedule
9. Summary

1. What is a fault current limiter (FCL)?

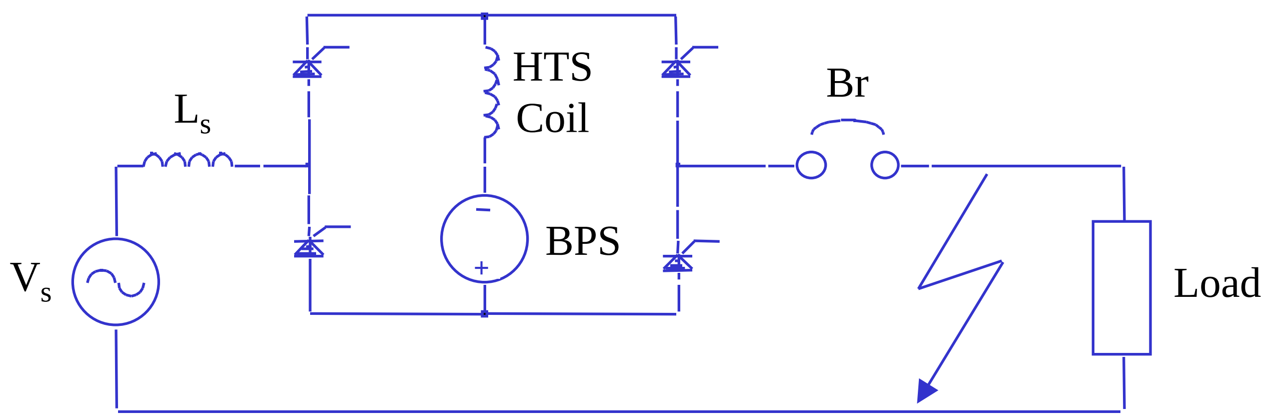
- A FCL is a device in an electrical system that reduces short circuit or fault currents to smaller current amplitudes
- A FCL provides fault current limiting actions in the first three to five cycles (50 to 80 ms) following a fault until the mechanical breaker interrupts the current
- A FCL provides disturbance isolation
- A FCL is a desired network component, which does not yet exist





Bridge-Type Fault Current Limiter

- Bridge-type FCL concept different from competing concepts
- Combination of HTS coil and power electronics circuits arranged in a bridge-type configuration
- Power electronics components assume voltage blocking and thus current limiting function during a fault condition, relieving HTS coil of those functions



- 15 kV prototype designed for 26 MVA rating

Features of the Bridge-Type FCL

- Limits first half cycle of short circuit current
- Fault current limiting is automatically initiated
- Steady-state fault current continuously adjustable from zero to peak value

  (Fault Current Controller, FCC)
- Operates as a solid-state breaker
- Automatically returns to rated operation after fault ceases
- Operates with or without bias power supply
- Suitable for multiple reclosures
- More versatile than alternative HTS FCLs
- Suitable for high power operation

FCC Located at Los Alamos Next to the Substation

Previous FCC Tests at SCE

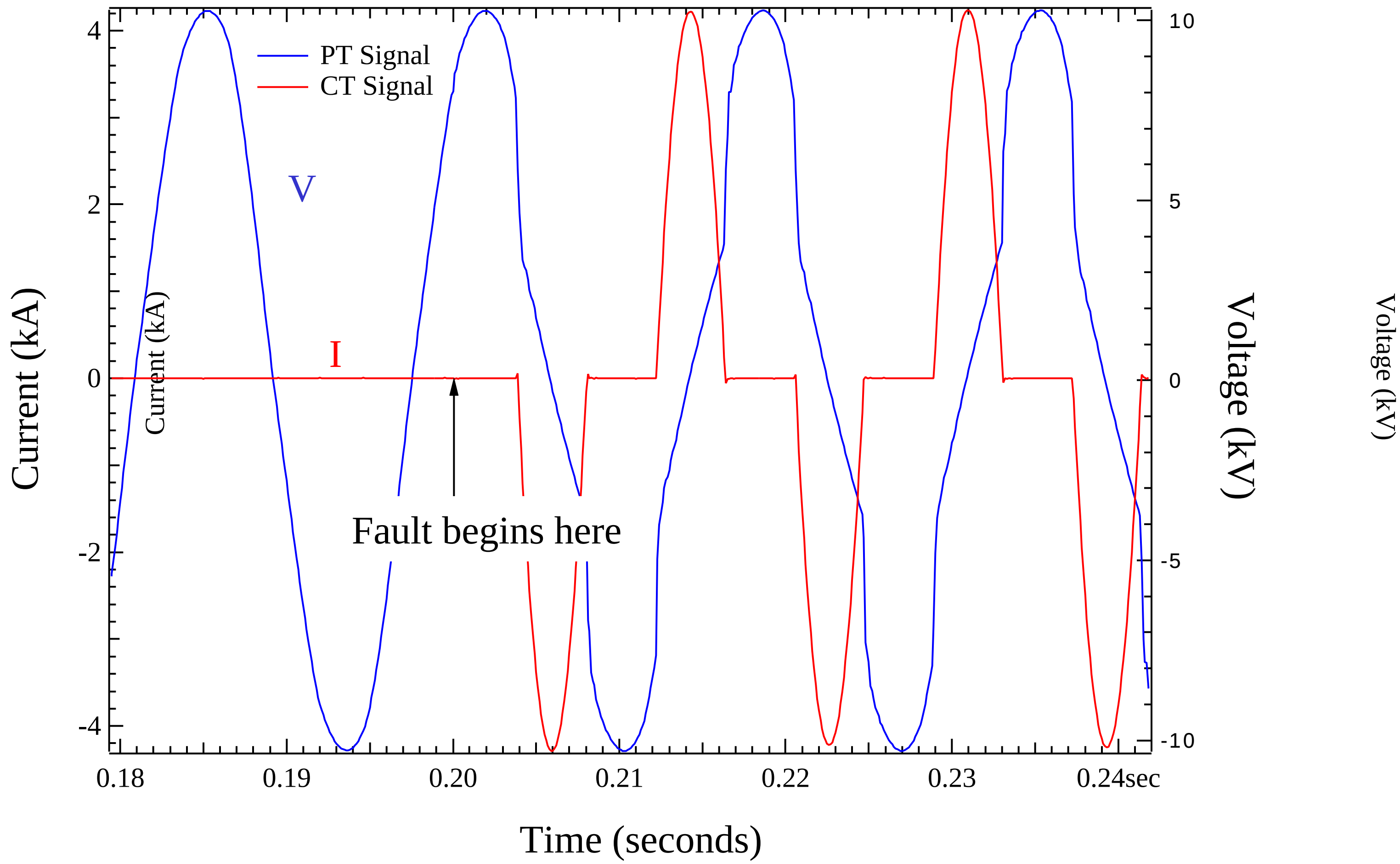
- Three-phase, 12.4 kV no load voltage test

  Voltage breakdown in vacuum system of phase A
- Single-phase current controller test with phase B

  Textbook results of current and voltage shapes - increase in vacuum pressure, current amplitudes too high
- Single-phase ac circuit breaker test with phase C

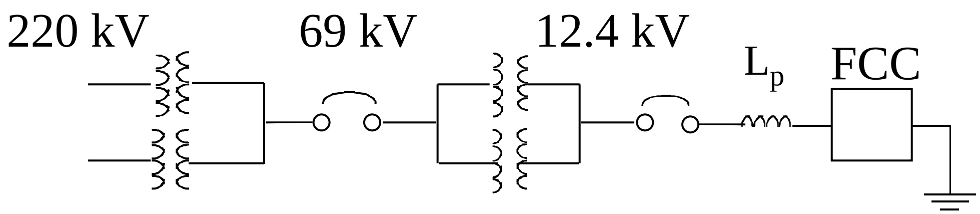
  Textbook results of current and voltage shapes - increase in vacuum pressure, current amplitudes too high

Current Controller Test - SCE Center Substation(7/11/99)



Analysis of Test Results

- **Test Set-up**



- **Analysis**

$$i = \frac{V_{peak}}{\omega L}\left[\sin(\omega t - \frac{\pi}{2}) - (\sin\alpha - \frac{\pi}{2})\right]$$

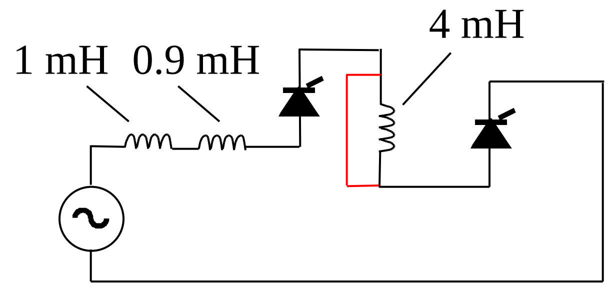
$$V_{peak} = \frac{12.5}{\sqrt{3}}\sqrt{2}\ kV = 10.2\ kV$$

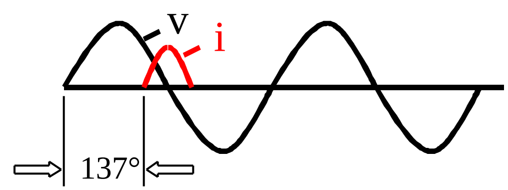
$$i_{peak\,meas} = 4.28\ kA$$

$$@\ \alpha = 137^\circ\ and\ 5.9\ mH \qquad i_{peak} = 1.22\ kA$$

$$@\ \alpha = 137^\circ\ and\ 1.9\ mH \qquad i_{peak} = 3.8\ kA$$

- **Simplified Circuit**





- **Conclusion**

HTS coil not in circuit

Internal fault occurred

2. Approach of Restoration Program

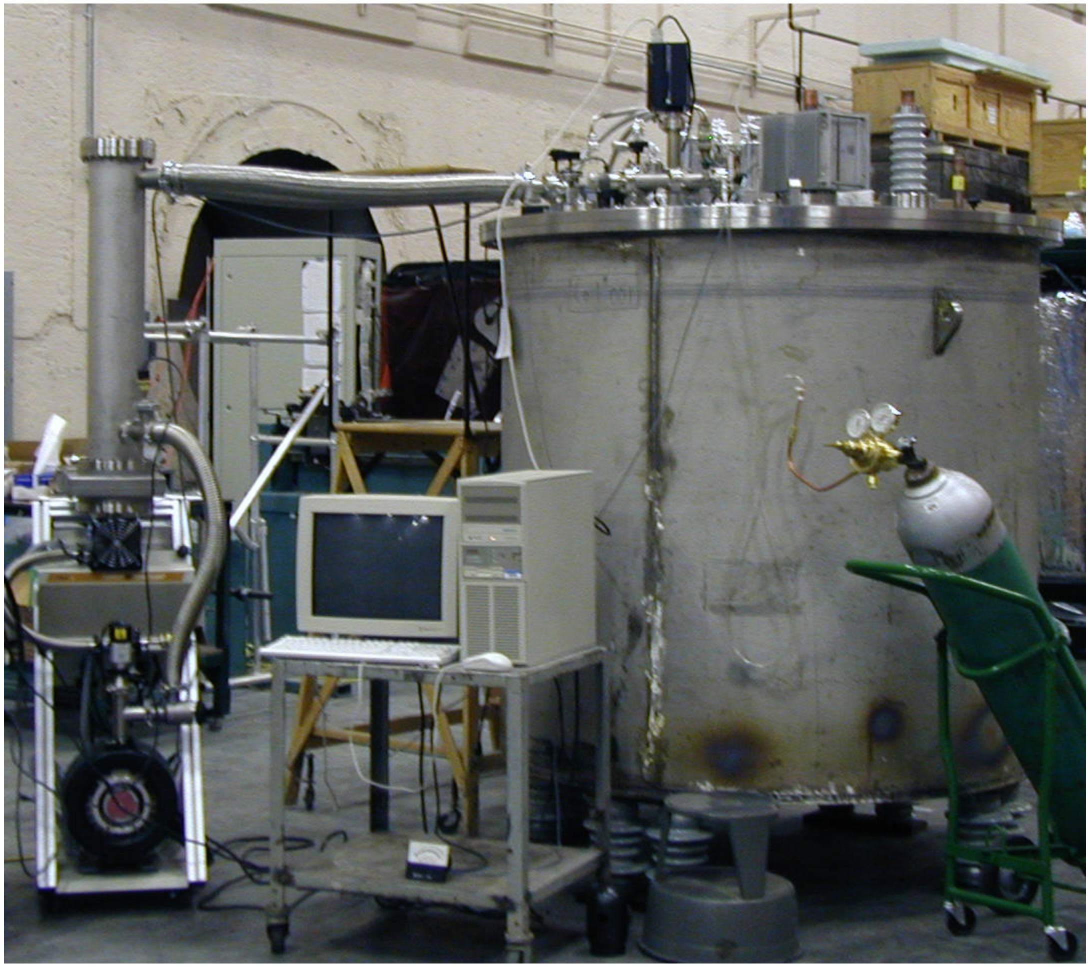
- Determination of scope of problem
- LANL - DOE agreement of FCC restoration step-by-step approach with cost effectiveness reviews
- Interest by industrial partners in program restoration
- Testing at Los Alamos (13.4 kV substation)
- GA personnel support

3. Result of Visual Inspection

- All three vessels were removed from FCC trailer and transported to power supply building.
- All three vessels were opened and inspected.
- Vessel of phase A has no visual damage

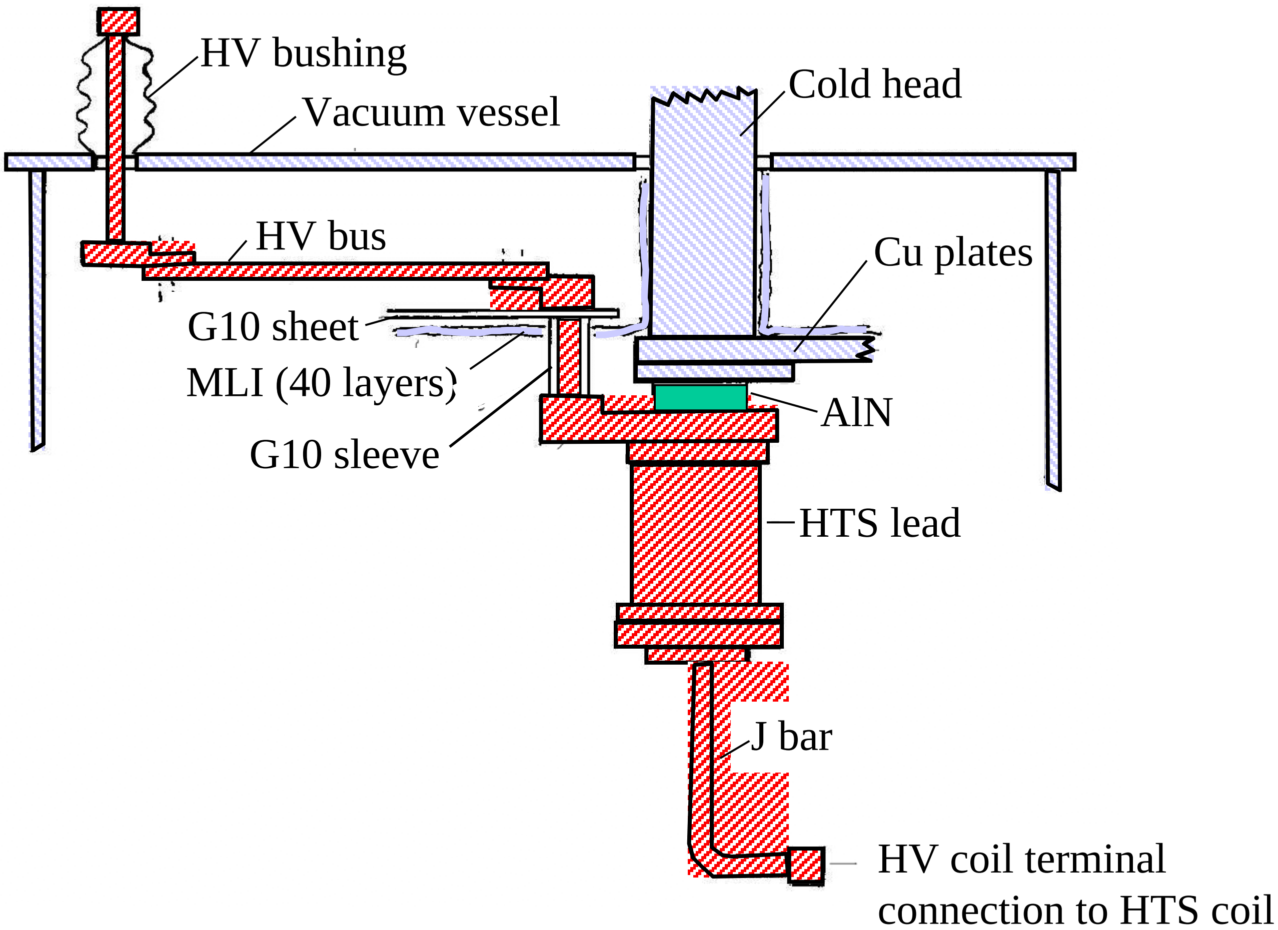
  A helium leak occurs at low temperatures
- Vessel of phase B and C have burn marks around the HV bus and the low voltage super-insulation; arcing occurred also to the vacuum vessel; location of flashover is the same
- No damage to HTS coils apparent
- No voltage breakdown at aluminum nitride component

Residual Gas Analysis Testing



Damaged Multi-Layer Insulation (MLI)

Schematic of the HV Bus



4. Failure Cause Determination

Joe Waynert

Panel of High Voltage Experts Assembled

(meeting January 22, 2001 at LANL)

Keith Nelson, RPI (chairman)	Ben McConnell, ORNL
Prit Chowdhuri, Tennessee TU	Isidor Sauers, ORNL
Andreas Neuber, Texas TU	
Kurt Nielsen, LANL	Bill Reass, LANL

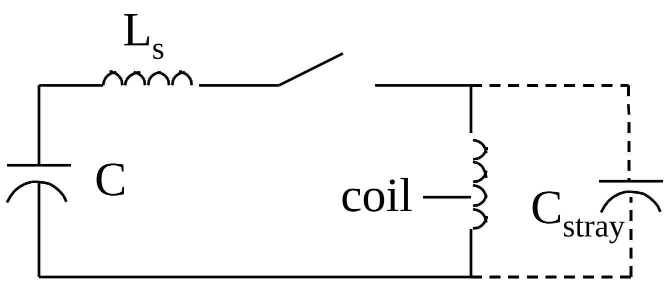
- Several potential failure mechanisms were identified
- A committee report was generated
- Committee suggestions led to a series of HV bus improvements

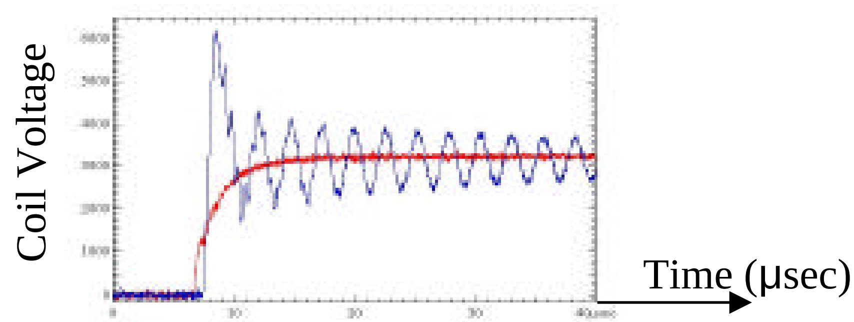
Potential Causes of Voltage Breakdown

- More-obvious causes of voltage flashover
  - Field enhancement by sharp corners
  - Presence of dirt particles
- Less-obvious causes of voltage flashover
  - Voltage doubling by resonance
  - Local gas cloud from ice evaporation
  - MLI evaporation from arcing
  - Reduction of breakdown voltage by magnetic field

Voltage Doubling by Resonance

- HTS coil may see twice applied voltage because of resonance between the source reactance and the coil stray capacitance. (textbook knowledge)
- Remedy: Low inductance capacitive snubber across coil terminals avoids voltage doubling, sizing of proper snubber important, minimize lead inductance
- Example:





- Fast voltage transients will be measured in experiment

Local Gas Cloud from Ice Evaporation

- Stray capacitance across the source inductor results in fast charging currents in the circuit, including the high voltage bus.
- Current amplitude might be above 50 to 100 kA according to simulations.
- Current time length very short, nanosecond time scale
- Ice, condensed on HV bus, evaporates, raises pressure locally, decreasing breakdown voltage.
- Remedy: Litz wire and insulation reduce surface current effects.

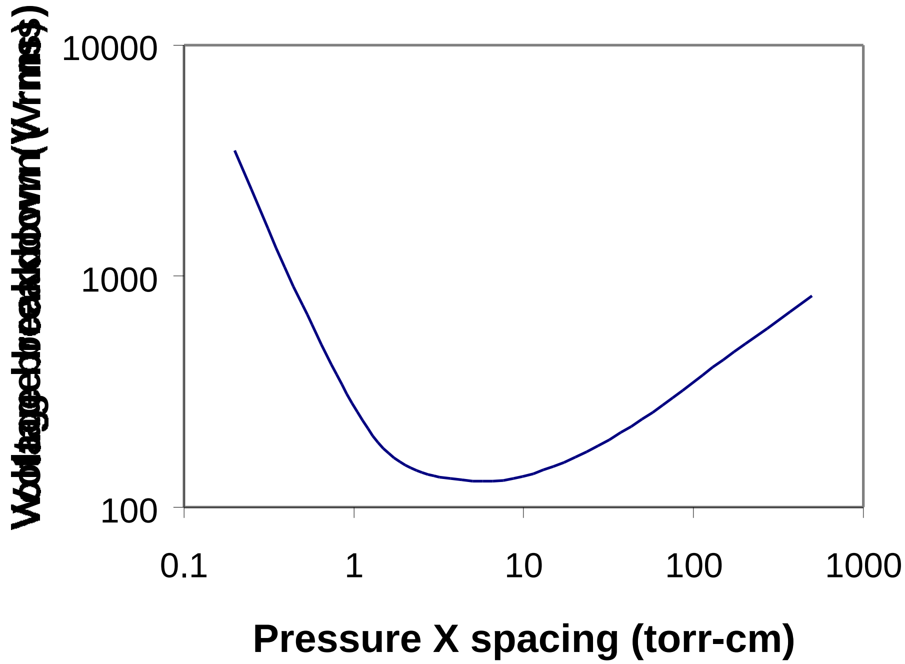
Local Gas Cloud from Vaporizing Unconstrained MLI

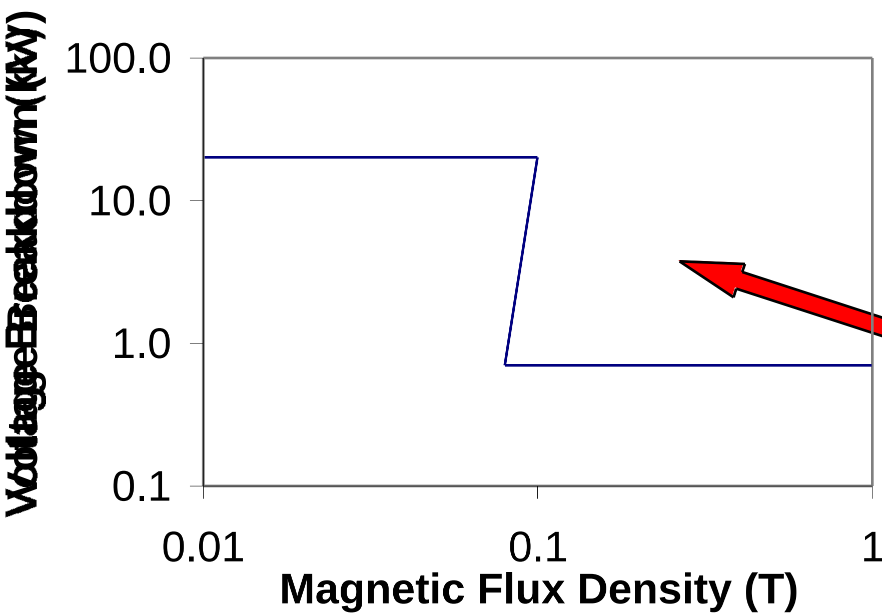
- Electric field displaces loose MLI.
- Arc to unconstrained MLI near penetration vaporizes material.
- Produces local gas cloud
- Reduces discharge strength
- Arc is initiated
- Vaporize 30 cm^2 to raise pressure to 10^{-4} torr (locally pressure much higher)

Effect of Self Magnetic Field

Paschen curve

10^{-6} torr X 5 cm





B field causes helical motion

Dramatic drop in V_b when diameter of circular motion is < mean free path

For FCC, 2 R ~ λ at 20 kA

Results of Failure Examination

- Identified a number of plausible failure mechanisms
- Failure mechanisms illustrate need to modify design of HV bus
- Have developed a design which addresses all identified issues

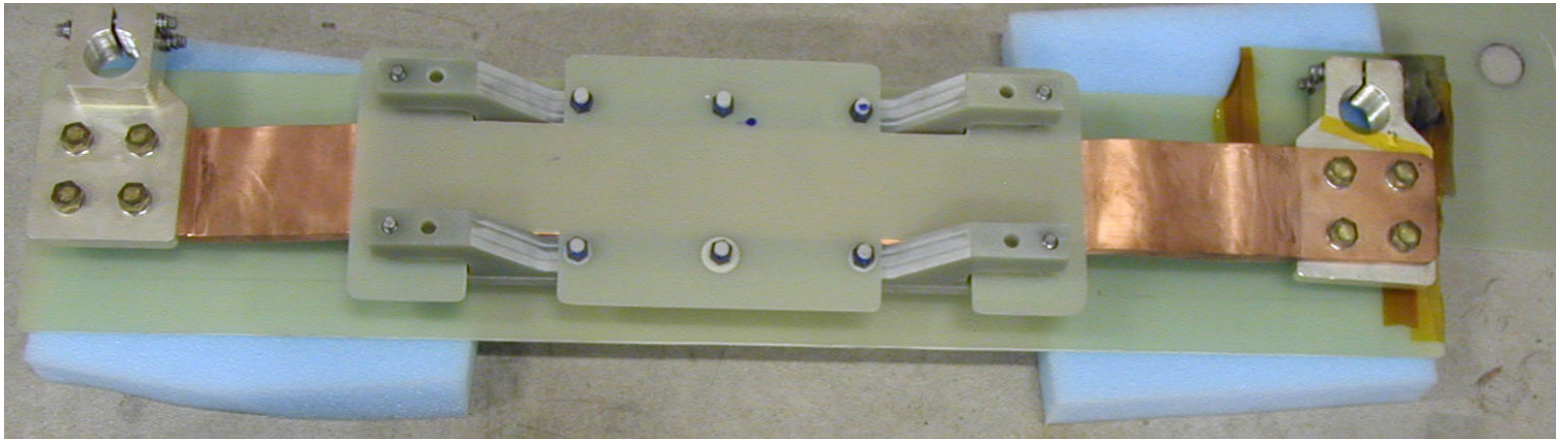
5. Vacuum and Cryogenic System Issues

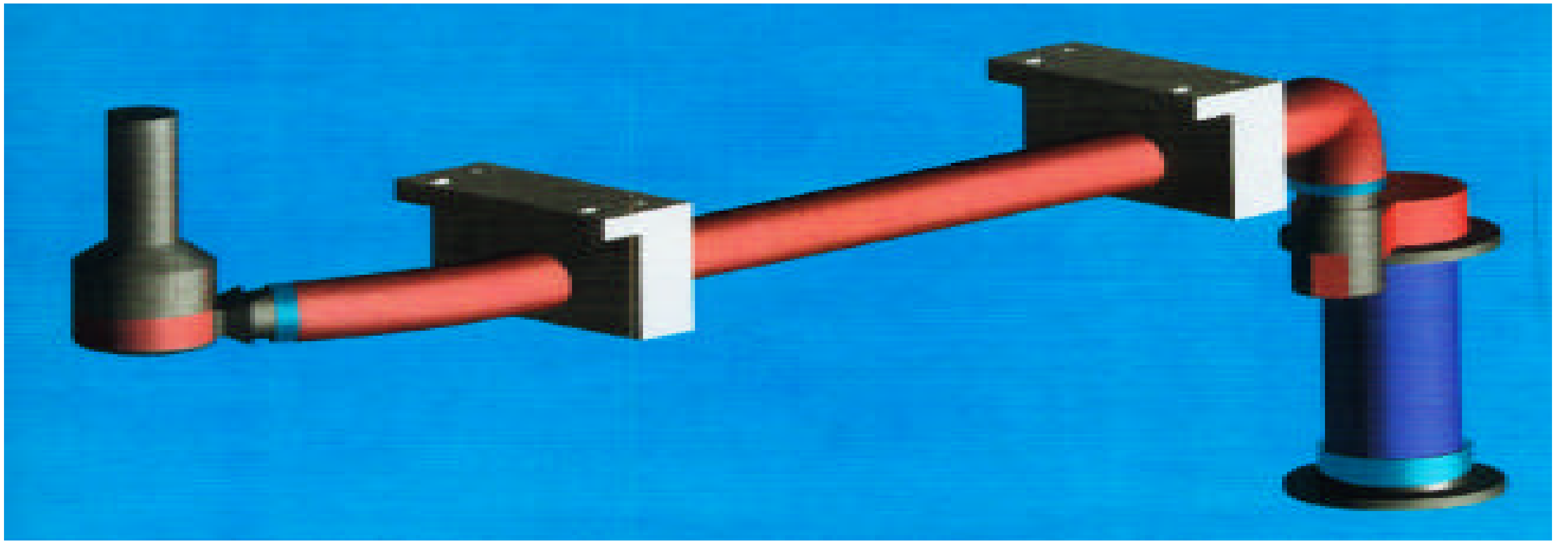
- He leak in one vessel and, in others, after arcing, high residual pressure
- No external pumping during operation (cryopumping)
- Need to maintain P < 5 x 10^{-5} torr
- Begun gas analyses to determine
  - long-term gas species and leak rates
  - amount and type of adsorbant(s)
- 10 documented cryocooler failures during substation tests
- Improve compressor ventilation
- General problem He contamination
- Established communications with Cryomech

6. New High Voltage Bus Design

- All identified failure mechanisms addressed in new design
- Existing technology reviewed to support new design
- Activities initiated to optimize bus performance
  – High pot testing in air
  – Surface breakdown measurements of AlN at Texas Tech University
  – Litz wire testing
  – Bushing design improvement
  – Electrical field simulations
  – Arc detection in vacuum vessel

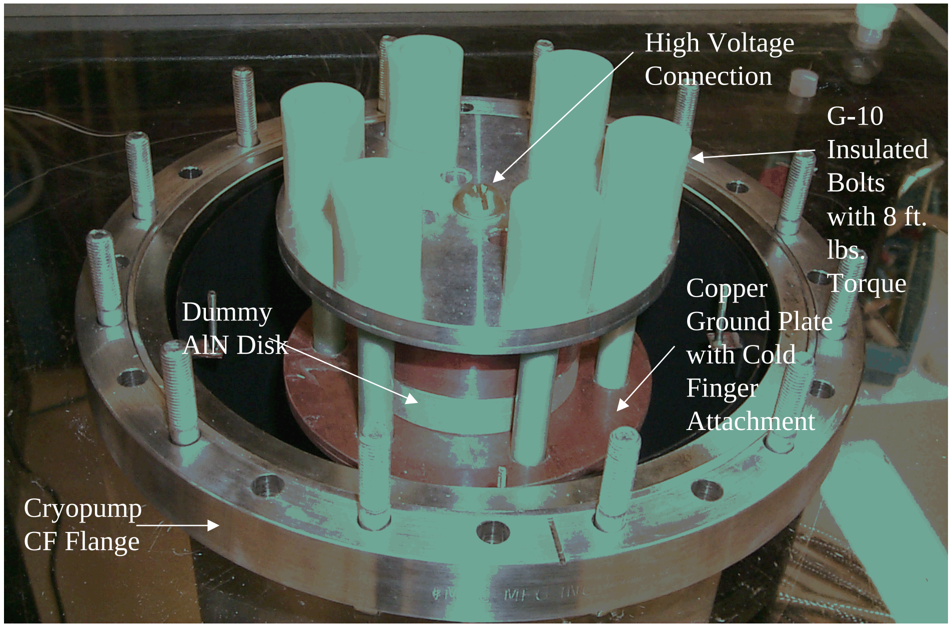
Old vs New Bus



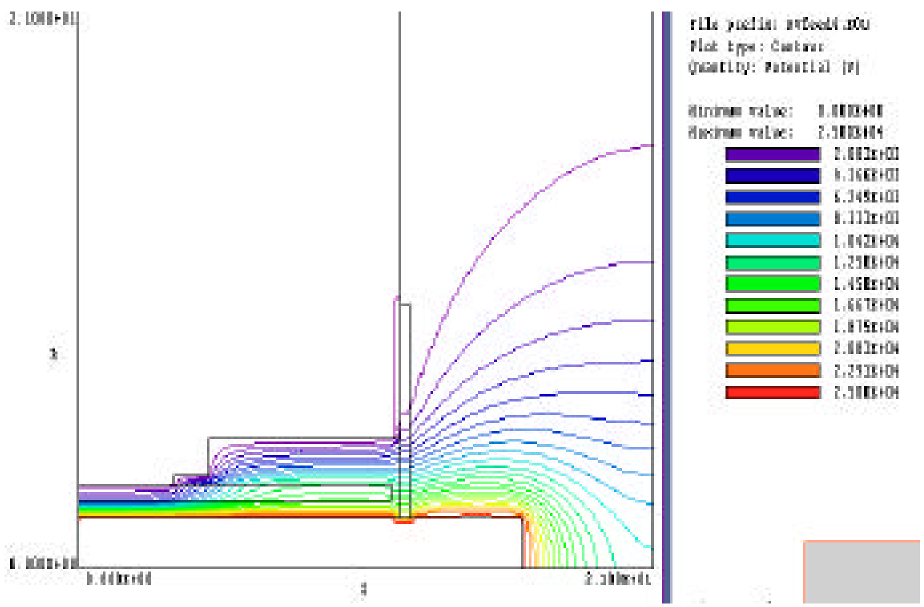


AlN Tests at Texas Tech University

- Measure the surface flashover voltage of an aluminum nitride disk at 40, 60, 80 K for 10^{-6}, 10^{-5}, 10^{-4} torr
- Repeat tests for disk with modified geometry



Examples of Support Capabilities



Finite element electrostatics analysis
for evaluating possible high field regions

High Resolution
CCD cameras
~$150 each

Camera for viewing arc discharge
in FCC vacuum vessel

7. Tests Planned at Los Alamos

- Substation tests of power electronics system using copper coil
- High voltage bus component tests
- Vacuum system residual gas analysis tests
- Capacitor bank test of HTS coil to rated voltage and current
- Single-phase and three-phase substation tests with FCC

8. Schedule

- Sept-Oct 2001 - Single-phase copper coil substation tests with all three phases
- Aug-Oct 2001 - High voltage bus tests
- Nov 2001 - Capacitor bank test with first repaired HTS unit
- Dec 2001 - Single-phase substation test with first repaired HTS FCC unit, load and short circuit test
- Feb-March 2002 - Single-phase substation tests with remaining two HTS FCC units
- April-May 2002 - Three-phase, FCC system load and short-circuit substation tests

9. Summary - FY01 Performance

Plans

- Identify failure mechanisms in FCC
- Determine feasibility of FCC repair
- Develop program for repair/enhancement
- Develop component and system test plan
- Investigate cryogenic and vacuum system performance issues

All FY01 Plans have been accomplished

Summary - FY01 Performance

Accomplishments

- Electrical failure mechanisms have been identified
- FCC repair feasible; restoration program plan developed
- New high voltage bus has been designed
- Testing of voltage breakdown of key component (AlN) has been initiated
- Laboratory site for component and system testing was selected
- Some components for substation tests have been specified and ordered
- Performance issues of cryogenic and vacuum systems have been identified and test plans developed

Summary - FY01 Results

- HTS coils from previous substation tests undamaged
- FCC electrical failure mechanisms identified (results from high voltage experts review committee)
- Texas Tech University work on surface breakdown voltage on AlN initiated
- New HV bus design addressing all failure mechanisms developed
- Cryogenic and vacuum system performance issues identified
- IGC test development support provided
- Test plans for components, subsystem, and system established
- Hardware specified and purchased for substation tests

Summary - FY02 Plans

- Complete design, fabrication, and test of new HV bus
- Demonstrate enhancements of cryogenic and vacuum systems
- Verify power electronic system performance in LANL substation
- Evaluate HTS coil performance in capacitor bank tests
- Perform single-phase and three-phase substation tests of FCC

Technology Integration

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